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Nuclear collision stopping of astatine atoms

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With 3 figures in the text

ABSTRACT

The ranges and range stragglings of astatine atoms stopped in aluminum and in silver have been measured. The reactions $Au^{197}(C^{12}, xn)At$ were used to provide astatine atoms with velocities near the Bohr velocity v_0, for which stopping is principally by nuclear collisions. The results are consistent with calculations involving an assumed potential of the screened field decreasing as r^{-2} from the nucleus for nuclear collisions.

Introduction

In his study of the penetration of atomic particles through matter, N. Bohr [1] has shown that atomic stopping can conveniently be considered in two parts: stopping by electronic collisions for particles with velocity $v > v_0$ and stopping by nuclear collisions for particles with velocities near or below v_0. Above the Bohr velocity $v_0 = \varepsilon^2/\hbar$, where ε is the electron charge, particles usually possess an ionic charge, but usually do not near and below this velocity. In the latter case, penetrations of the electron clouds of the particle and target atoms cause scatterings in the screened fields of the nuclei. The large energy exchanges and large scattering angles of these collisions result in unusually large straggling in range and in a range–energy relation different from that of the usual stopping by electronic collisions.

In the screened fields of importance in nuclear scatterings, the field is expected to decrease more rapidly with radius r from the nucleus than a Coulomb field. N. Bohr [1] considers a potential

$$P(r) = \frac{k_2}{r^2} \qquad (1)$$

to apply for these conditions, where $k_2 = Z_1 Z_2 \varepsilon^2 a/e$. Here, Z_1 and Z_2 are the atomic numbers of the colliding particles and the screening parameter is $a = a_0/\sqrt{Z_1^{2/3} + Z_2^{2/3}}$. The radius a_0 of the hydrogen atom is $a_0 = \hbar^2/\mu\varepsilon^2$, where μ denotes the electronic mass. Using this field and the limiting impact parameter

$$p_c = \frac{2\,|k_2|\,(M_1 + M_2)}{M_1 M_2 v^2} \qquad (2)$$

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used by N. Bohr [1], Lindhard and Scharff [2] find the range due to nuclear collisions to be given, to close approximation, by

$$R = \frac{e}{\pi^2 a_0^2} \frac{M_1 + M_2}{2 \mu N} \frac{v^2}{v_0^2} \frac{\sqrt{Z_1^{2/3} + Z_2^{2/3}}}{Z_1 Z_2}, \tag{3}$$

where M_1 and M_2 are the masses of the colliding particles and N is the density of stopping atoms. Also, they find the straggling ϱ in the distribution $W(R)$ of the range R about R_0,

$$W(R) = \frac{1}{\varrho R_0 \sqrt{2\pi}} \exp\left[-\frac{(R_0 - R)^2}{2 \varrho^2 R_0^2}\right], \tag{4}$$

to be

$$\varrho^2 = \frac{2 M_1 M_2}{3 (M_1 + M_2)^2} \tag{5}$$

to a close approximation.[1] It is seen that the range expression (3) is essentially the same as equation (5.4.2) given by N. Bohr [1]; however, the magnitude of ϱ^2 resulting from (5) is just half the value quoted by Bohr in his equation (5.4.3).

Of significance in these calculations is the fact that p_c does not enter into the determination of the straggling ϱ in (5). For this reason, comparison of the range straggling from nuclear collisions with (4) and (5) is a test of the potential (1) of the screened atom used in the calculations.

A considerable part of the range of fission fragments remain when the fragment velocity becomes v_0. Several observations [3, 4, 5] of the straggling of identified nuclides from fission qualitatively confirm these stopping principles. However, the complications of the variation of the initial energies of the fragments and of the fraction of the range in which electronic collisions predominate made difficult a quantitative evaluation of these measurements in terms of nuclear collisions.

In the present measurements, recoil atoms of astatine with velocities near v_0 were used to determine the ranges for stopping predominantly by nuclear collisions. The use of these recoil ranges in separation and identification of heavy elements formed by bombardment with energetic particles has previously been discussed by Leachman *et al.* [6].

Method

For the production of astatine atoms, gold was bombarded with high energy carbon ions. The reactions $Au^{197}(C^{12}, 4n)At^{205}$ and $Au^{197}(C^{12}, 6n)At^{203}$, which have been studied by Hollander [7], were used in internal probe bombardments in the 225-cm cyclotron at the Nobel Institute of Physics. The carbon beam was obtained by accelerating $C^{12\,(4+)}$ ions.

The mechanical arrangement of the gold target deposit and the stopping foils in the cyclotron probe is shown in Fig. 1. The target was evaporated gold, usually 90 μg/cm^2 thick, on an aluminum backing 2.9 mg/cm^2 thick. Since the combined momenta of the several neutrons emitted in the reactions can be neglected, the astatine atoms are considered to continue with the same momentum as the carbon ions.

The ranges of astatine atoms stopped in the stopping foils were determined by the alpha activities in the foils. After the bombardments, the alpha activities of the

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[1] In equation (4) and in the following ϱR_0 is identical with the standard deviation for the range distribution.

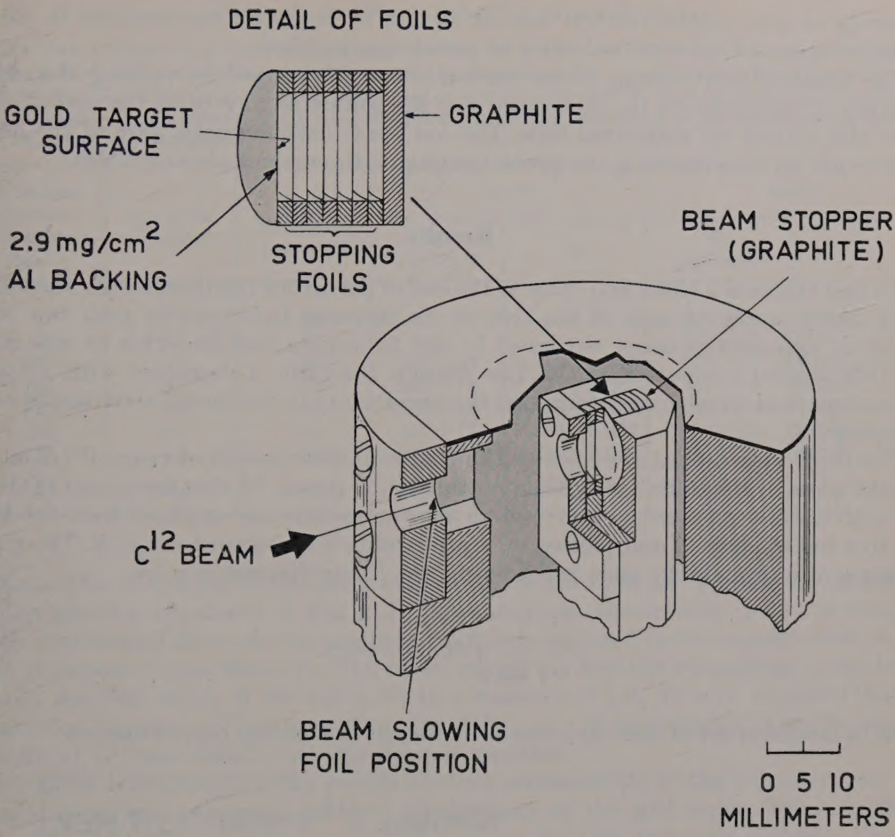

Fig. 1. Schematic representation of the probe used in the bombardments. The target, stopping foils, and beam stopper are shown, but some other components of the probe have been omitted for simplicity.

stopping foils were followed by conventional alpha detectors. No processing of the foils was required. The isotopes of astatine were identified by the 25-minute half-life of At^{205} and the 7-minute half-life of At^{203} reported by Barton *et al.* [8] and recently confirmed by Burcham and Haywood [9], but because of detector difficulties were not identified by the characteristic alpha energies.

The target deposit of gold was evaporated on rolled aluminum foil. A sample of the gold target was chemically stripped from the aluminum and remounted on glass for thickness measurements, obtained through the use of a multiple-beam interferometer and by a determination of the sample's opacity to light. The catcher foils were prepared by evaporating aluminum or silver on glass on which a thin layer of wetting agent had previously been deposited either by dipping or by evaporation. With these preparations, the metal foils were stripped from the glass by introducing the glass slowly into water. While still floating on the water, the foils were mounted on supporting rings by zapon. A sample of each foil was mounted on glass for thickness measurements to about 5 % accuracy with a multiple-beam interferometer. The accuracy of this optical method was confirmed by control measurements in which metal evaporated on standard discs of metal was weighed.

The bombardment energy of the carbon ions was changed by varying the radial position of the probe in the cyclotron. For the lowest energy runs, the carbon ions were also slowed by aluminum foils. The ion beam currents used were of the order of 10^{-2} μA for ions reaching the probe opening with energies above 80 MeV.

Results

To find the initial alpha activities at the end of the carbon bombardments, the measured decay curve of each of the five or six stopping foils used in each run were fitted by exponential decay curves of 7- and 25-minute half-life. This fit was done by IBM digital computers at the Los Alamos Scientific Laboratory with a least-squares method which also determined the uncertainty in the initial activities of each stopping foil.

The fit of these initial activities to the Gaussian distribution of range $W(R)$ of (4) was by plots of the initial activities on probability paper. In this treatment of data, the activities (normalized to unity) of an astatine isotope are summed from the first foil to a foil of range R and plotted on a probability scale against range R. The numbering y of a probability scale is related to the linear dimension u by

$$y = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} dt \exp(-t^2/2). \qquad (6)$$

Thus, a Gaussian set of data appears as a straight line in this representation.

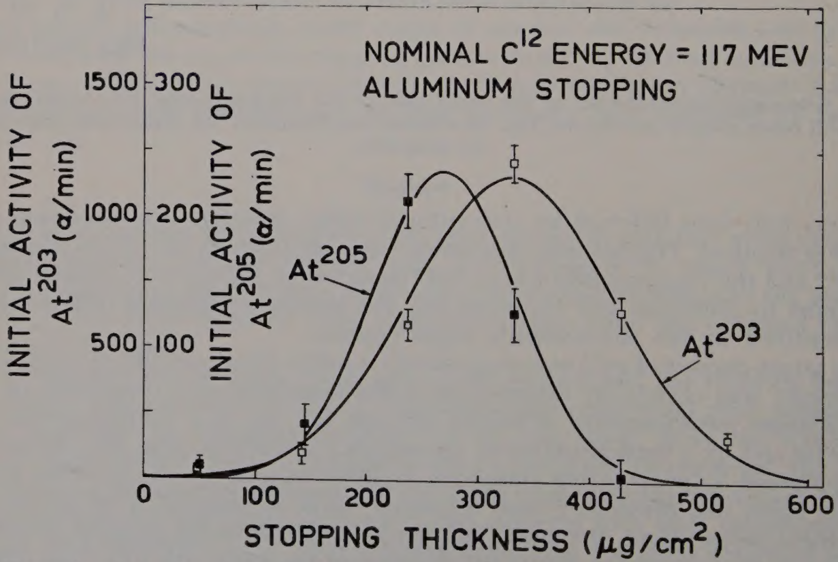

Fig. 2. Example of the fits of foil activities to Gaussian curves. Ranges in the gold source are not included in these data. Open squares are of the 7-minute At^{203} activity; closed squares are of the 25-minute At^{205} activity.

Table 1. Astatine ranges and straggling.

The mean range R_0 and the straggling ϱ include the aluminum equivalent of the half thickness of the gold source determined by the use of (3). Uncertainties are estimated errors as obtained from plots of foil data on probability paper and do not include the 5 % uncertainty in foil thickness. The nominal carbon energy has been determined from the frequency of the accelerating voltage and from probe conditions.

Nominal carbon energy (MeV)	Stopping element	Foil thickness (μg/cm^2)	At^{203}		At^{205}	
			R_0 (μg/cm^2)	ϱ	R_0 (μg/cm^2)	ϱ
67	Al	85			242 ± 10	0.256 ± 0.035
83	Al	85			251 ± 11	0.271 ± 0.034
105	Al	95	309 ± 24	0.289 ± 0.078	271 ± 8	0.298 ± 0.018
105	Al	95	285 ± 14	0.299 ± 0.067	261 ± 11	0.273 ± 0.055
117	Al	95	347 ± 15	0.260 ± 0.030	287 ± 19	0.221 ± 0.043
128	Al	95	357 ± 12	0.290 ± 0.027	269 ± 19	0.240 ± 0.074
128	Al	85	343 ± 10	0.250 ± 0.044	281 ± 17	0.269 ± 0.045
128	Ag	165	476 ± 30	0.402 ± 0.053	434 ± 20	0.390 ± 0.049

Examples of the fits of Gaussian expressions to the data as obtained by this probability plotting are shown in Fig. 2. In these analyses, the activity, which is continuously distributed through the stopping foils, is considered to be concentrated at the half thickness. From these fits, the mean ranges R_0 and the stragglings ϱ are determined, the half width of the curve being a measure of ϱR_0. It is to be noted that R_0 is greater for the At^{203} isotope than for At^{205}, as is to be expected from the greater energy of C^{12} associated with the former reaction.

In Table 1 are compiled the results of these Gaussian fits to the foil activities. The results have been corrected for the half thickness of the gold source by using (3) to determine the relative stopping of gold compared to the stopping material. Corrections were about 7 % for the 90-μg/cm^2 thickness of the gold target used in all bombardments except the 67-Mev bombardment, for which 48 μg/cm^2 of gold resulted in a 4 % correction.

In Fig. 3 is shown the dependence of the mean ranges R_0 upon the nominal carbon ion energy as determined from the probe position and the frequency of the accelerating voltage and from calculated energy losses of carbon ions in aluminum. The small variation of range of, in particular, At^{205} with the nominal carbon ion energy is to be noted. This effect can be explained by considering the narrow span of energies for which the cross section of the reaction is appreciable. Information on this energy span can be obtained from the calculations of (p, xn) cross sections in heavy elements by Jackson [10], which are confirmed by the measurements of Bell and Skarsgard [11]. The widths of the peaks of their excitation functions for the $4n$ reaction are considerably narrower than the span of nominal carbon energies covered by all the different bombardments. Consequently, the results shown in Fig. 3 indicate that the carbon ions used in each bombardment have been widely spread in energy, perhaps partly as a result of ions formed outside the ion source. This is also supported by later investigations of the energy spectrum of the carbon ion beam. Thus, the explanation for the nearly constant ranges R_0 for a wide span of bombardment conditions is that the small span of energies in the excitation function of the reaction makes preferen-

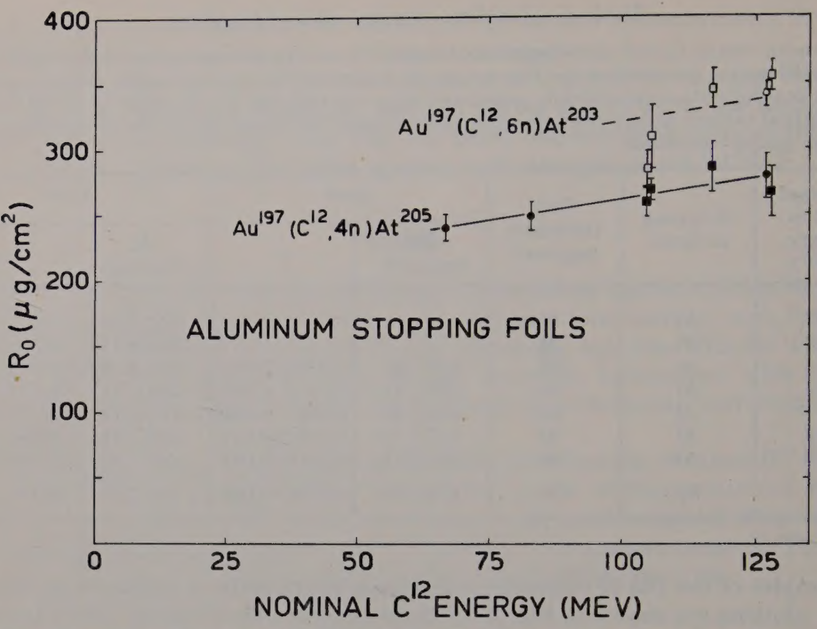

Fig. 3. The mean range R_0 of astatine isotopes for different nominal values of the carbon ion energy. The range includes the aluminum equivalent of the half thickness of the gold source. Open symbols are of At^{203}; closed symbols are of At^{205}. Squares are for bombardments with stopping foils of 95 $\mu g/cm^2$; circles are for foils of 85 $\mu g/cm^2$. The nominal energies have been determined from the probe position and the frequency of the accelerating voltage and from foil slowing. They give only an approximate representation of the carbon energies involved in the bombardments. The dotted curve is somewhat arbitrarily drawn due to the small number of experimental points.

tially effective these energies in the broad energy spectrum of carbon ions in any bombardment.

A comparison of the observed ranges with the range expression (3) is difficult, principally because the energies of the peak in the excitation functions for the heavy ion reactions used are unknown, and also because carbon ion energies in the bombardments are not well determined. To make a qualitative comparison in Table 2 we first assign representative ranges from Table 1 and Fig. 3. Then from (3) and momenta considerations of the reaction the corresponding bombardment energies of the carbon

Table 2. Bombardment energies E_c of carbon ions derived from astatine ranges by the use of (3).

Ranges R_0 are representative ranges estimated from Table 1.

	Al stopping		Ag stopping	
	At^{203}	At^{205}	At^{203}	At^{205}
R_0 (mg/cm^2)	0.32	0.25	0.46	0.40
E_c (MeV)	70	54	59	51

ions are determined. The estimate of the representative ranges in silver is necessarily inaccurate, being estimated from one bombardment only. On the other hand, suggestions of most probable carbon ion energies obtained from a different analysis are about 80 Mev for the At^{203} reaction and about 65 Mev for the reaction producing At^{205}. These are estimated from the excitation of the compound nucleus as derived from the atomic masses in the reaction and from current concepts of neutron boilout. The similarity to the energies of carbon ions deduced in Table 2 thus indicates a qualitative agreement between the range equation (3) and measurements, but the qualitative nature of this comparison is emphasized.

Comparisons of the range stragglings ϱ from Table 1 (corrected as below) with values from (4) and (5) provide more significant evaluations of the theory of stopping by nuclear collisions. The experimental values of ϱ, properly corrected for the effect of the span of carbon energies inducing the reactions, are independent of uncertainties in carbon ion energies.

The weighted average values from Table 1 both for At^{203} and for At^{205} in aluminum is $\varrho = 0.28$. In both cases, the average deviation of the ϱ values in Table 1 from the weighted average is 0.02. The measured stragglings include experimental effects in addition to the nuclear collisions being investigated. Equivalent ϱ values of these straggling effects can be estimated: 0.10 for the recoil range effect of the span of carbon ion energies inducing the reactions, as estimated from the cross-section calculations of Jackson [10]; 0.10 for the effect of the thickness of the aluminum foils, as obtained by the use of Sheppard's correction [12]; and 0.06 for the gold source thickness. The observed $\varrho = 0.28$ is reduced to $\varrho = 0.23$ by the removal of these other straggling effects. The agreement of the latter with $\varrho = 0.26$ from (5) for astatine atoms in aluminum is satisfactory.

A similar agreement is found for the straggling in silver. The ϱ value 0.40 (± 0.05) from Table 1 for the single bombardment with silver stopping foils is reduced to $\varrho = 0.36$ when effects of the energy spread and foil thickness are removed as above. The latter ϱ value is in satisfactory agreement with $\varrho = 0.39$ from (5).

It seems reasonable to conclude from these straggling data, particularly from the aluminum stopping data, that the r^{-2} form of the screened potential (1) used in the derivations of nuclear collision expressions is effective in these collisions.

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